

# Minimal Flavor Violation at Large $\tan\beta$

CHRISTOPHER KOLDA

*Department of Physics, University of Notre Dame  
Notre Dame, Indiana 46556, USA*

## ABSTRACT

I review briefly the notion of minimal flavor violation and its application to supersymmetry, with a special emphasis on a class of operators, so-called Higgs penguins, which can generate new and interesting flavor signals at large  $\tan\beta$ .

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## 1. Care and Feeding of the Higgs Penguin

If it were not for the gauge hierarchy problem, there would be no reason to expect the Standard Model (SM) of particle physics to be modified at scales near those being explored today. Extensions of the SM at the weak scale face such high hurdles that one could easily argue that new physics simply will not be found there. These hurdles include precision measurements of the electroweak oblique parameters and the non-observation of flavor-changing neutral currents (FCNCs), CP violation, or baryon number violation at levels that one would expect from most models of new, weak-scale physics.

Nonetheless the gauge hierarchy problem needs a solution, and it needs a solution at the weak scale. This tension is the central problem in theoretical particle physics right now. The best solution to the hierarchy problem, supersymmetry (SUSY), is only partially successful in overcoming the constraints listed above. In particular, it has great difficulty with the FCNC and CP violation constraints. One would not expect “generic” new physics which couples non-universally to flavor (such as SUSY) below scales of 10's to even 1000's of TeV. Yet SUSY must be below 1 TeV in order to solve the hierarchy problem.

In generic new models of physics, there is one very attractive approach to preventing large new flavor signals: we can require that the model be *minimally flavor violating* (MFV). Such a condition has been defined in many ways over the years, but I have in mind here the definition proposed by Ref. [1] in which one imposes a global  $SU(3)^5$  flavor symmetry on the particle spectrum and interactions, under the added assumption that only the Yukawa matrices violate the symmetry. In such a picture a spurion analysis reveals exactly what kinds of FCNC signal can and cannot show up.

Usually one can make a statement in MFV models that no new operators arise which are not already in the SM and that new contributions to SM operators are suppressed by the same CKM factors that suppress the SM contributions. Thus new MFV physics changes SM predictions for FCNC processes by  $O(1)$  at best. A very special case is CP-violating asymmetries where one can go farther and show that MFV models cannot change these at all! The minimal SUSY Standard Model (MSSM) is not necessarily an

MFV theory, but certain classes of MSSM “models” fit the mold. These include models with unified scalar masses (mSUGRA models), anomaly-mediated and gauge-mediated models. For example, in the mSUGRA models flavor violation only enters through the renormalization group equations (RGEs). For example, the left-handed scalar mass RGEs have a general form:

$$\frac{d}{dt} (m_{\tilde{Q}}^2)_{ij} \propto a \mathbf{1}_{ij} + b (Y_U^\dagger Y_U)_{ij} \quad (1)$$

where the up-quark Yukawa matrix,  $Y_U$ , is non-diagonal.

However the claim that no new operators arise, and that all SM-like operators have a SM-like flavor suppression, does not hold in the MSSM. There is a hidden assumption underlying the original claim: that the low-energy effective theory is the *minimal* Standard Model; that is, it contains only a single Higgs field. If the low energy theory is a two Higgs doublet model, then new operators arise which can generate large, new FCNCs. Such is the low energy limit of the MSSM when the second Higgs doublet is not too heavy (*i.e.*,  $m_A \not\gg m_Z$ ).

How does this show itself? It is convenient to work in a basis in which

$$Y_D = \text{diag}(y_d, y_s, y_b), \quad Y_U = V^\dagger \times \text{diag}(y_u, y_c, y_t) \quad (2)$$

where  $V$  is the usual CKM matrix. The leading flavor changing operators must all scale as  $(Y_U^\dagger Y_U)_{ij} \propto y_i^2 V_{3i}^* V_{3j}$ . There could also be operators involving powers of  $Y_D$ , but in a single Higgs model these are always suppressed by powers of  $m_b/m_t$ .

But because the MSSM is a two Higgs model, the suppression is instead  $(m_b/m_t) \tan \beta$ , which can be  $O(1)$  if  $\tan \beta$  is large. For example, a one-Higgs model would never generate a large  $\bar{b}_R s_L$  operator because it would always be suppressed by  $m_b$ . But in the MSSM, it is instead suppressed by  $m_b \tan \beta$ , which need not be a suppression at all.

It is by now well known that in the MSSM such operators can arise and be important. New flavor-conserving  $\bar{b}_r b_L$  operators were discussed most explicitly by Hall *et al.* [2], though there existed a long prehistory in which a number of authors took note of their existence [3]. The flavor-violating operators were discovered and studied much later. The discussion here is based on the paper of Babu and Kolda [4], though other early related discussions can be found in Refs. [5]. (A recent review, with a more complete list of references, can be found in Ref. [6].)

There are two approaches commonly used to calculate the new FCNC operators: the effective Lagrangian approach, or a Feynman diagrammatic approach. The former has the advantage of resumming the leading contributions from several orders of diagrams and is process independent. The latter, though more unwieldy, demonstrates the new contributions explicitly in diagrams which are reminiscent of penguin diagrams, except with a Higgs boson replacing the vector boson. Thus the name “Higgs penguins” has arisen to describe this new physics. Nonetheless we will follow the simpler effective Lagrangian approach pioneered in Ref. [4].

In the effective Lagrangian approach one integrates out the SUSY partners (but not the second Higgs doublet) at the scale  $M_{\text{SUSY}}$ . In doing so, an effective  $\bar{d}_{Ri} d_{Lj} H_u^c$  interaction is generated. For  $i \neq j$ , there are two leading diagrams that must be included: a 1-loop

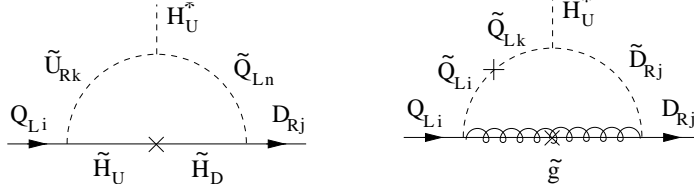


Figure 1: The two leading diagrams in the calculation of the effective  $\bar{b}_{RL}H_u^c$  interaction. The cross in the second diagram represents a one-loop flavor mixing contribution from the RGEs.

Higgsino diagram and a 2-loop gluino diagram (see Fig. 1). Both generate the new operator  $\bar{Q}_L(Y_U Y_U^\dagger)Y_D D_R H_U^c$ . The Higgsino diagram generates a coefficient of order  $1/(16\pi^2)$ , while the gluino diagram generates a coefficient of order  $\alpha_s/(9\pi^3)\log(M_X/M_{\text{SUSY}})$ . If the log is large, then this 2-loop contribution can be as important as the 1-loop piece.

When the  $H_u$  field gets a vev, these operators generate new contributions to the  $d$ -quark mass matrix. For example, keeping the  $s$ - and  $b$ -quarks only, one has a mass matrix

$$-\mathcal{L} = \begin{pmatrix} \bar{s}_R & \bar{b}_R \end{pmatrix} \begin{pmatrix} y_s v \cos \beta & 0 \\ \epsilon y_b y_t^2 v \sin \beta & y_b v \cos \beta \end{pmatrix} \begin{pmatrix} s_L^0 \\ b_L^0 \end{pmatrix} \quad (3)$$

where  $\epsilon$  is the sum of the two contributions discussed previously. Diagonalizing this matrix requires the  $s_L^0$  and  $b_L^0$  to mix at an angle

$$\sin \theta \simeq \epsilon y_t^2 \tan \beta \quad (4)$$

which can be  $O(1)$  if  $\tan \beta$  is large. Thus we have a brand new flavor-changing parameter,  $\sin \theta$ , which does not correspond to any parameter of the SM.

Where is this new physics important? The biggest effect comes in purely leptonic  $B_s$ -meson decays through the operator  $(\bar{b}_{RL})(\bar{\ell}_R \ell_L)$ . Because of the chiral structure on both sides, this operator must scale as  $y_b y_\ell$ , which implies a  $\tan^2 \beta$  dependence to the operator. But the angle  $\theta$  has its own  $\tan \beta$  dependence, so the entire operator scales as  $\tan^3 \beta$ . Of course, the operator is dimension six and so must fall as  $1/\Lambda^2$ . Here we can interpret  $\Lambda = m_A$  since in the limit  $m_A \rightarrow \infty$ , our model contains only a single Higgs and is therefore immune to new operators. For the remainder of this talk I will review what is known about the leading channels for discovering this SUSY “violation” of minimal flavor violation, and what we may learn from them.

## 2. Experimental Signatures

$B_{s,d} \rightarrow \mu\mu$ : This is the gold-plated mode. The SM rates are GIM- and helicity-suppressed ( $B(B_s \rightarrow \mu\mu) \simeq 4 \times 10^{-9}$ ), so the SUSY rate can be several orders of magnitude larger than the SM. This mode is easily studied at the Tevatron where plentiful  $B_s$  mesons are produced and their decays to muons are easy to tag. In fact, this may provide our best hope for finding SUSY at the Tevatron, as the Tevatron is sensitive to rates down to about  $10^{-7}$  over the next few years. On the other hand  $B$ -factories, which make  $B_d$  but not  $B_s$ , suffer a  $(V_{td}/V_{ts})^2$  suppression in their rates, which is enough to put them outside the interesting range at present.

$\mathbf{B}_{s,d} \rightarrow \tau\tau$ : While this is the ideal mode theoretically, beating  $B \rightarrow \mu\mu$  by  $(m_\tau/m_\mu)^2$ , it is not a very good channel experimentally. This could be studied at a  $B$ -factory with a large sample of fully reconstructed  $B_d$ 's, but that would require SuperB factory luminosities.

$\mathbf{B}_d \rightarrow \mathbf{X}_s \mu\mu$ : In this 3-body decay, the SM contribution is no longer helicity suppressed, eliminating one of the big advantages of the  $B_s \rightarrow \mu\mu$  mode. However SUSY can still generate  $O(1)$  corrections to the branching fraction. In order to cancel the large uncertainties in the SM rate calculation, Hiller and Krüger [7] have suggested a search for deviations in  $B(B_d \rightarrow K\mu\mu)/B(B_d \rightarrow Kee)$ . With the appropriate kinematic cuts, the SM prediction for this ratio is known to better than 0.01%. Though current experimental data does not constrain the Higgs penguin as strongly as  $B_s \rightarrow \mu\mu$ , it is approaching that level of utility. Plus it provides information from the  $B_d$  sector which would be a nice consistency check on the Higgs penguin picture.

$\mathbf{B}^0 - \bar{\mathbf{B}}^0$  mixing: In MFV models, even those with two Higgs doublets, this can be shown to be suppressed beyond naive power counting [1]. However contributions do arise at  $O(m_s/m_b)$  [8] and at two loops [4]. Buras *et al.* [8] have found that, given CDF bounds in  $B_s \rightarrow \mu\mu$ , the Higgs penguin contributions to  $B_s - \bar{B}_s$  mixing could suppress  $\Delta M_s$  by as much as 50% from its SM prediction. They also found the suppression to be highly correlated with the rate for  $B_s \rightarrow \mu\mu$ , suggesting another nice consistency check on the Higgs penguin scenario.

There is no single definition of minimal flavor violation in the leptonic sector. Applying the same logic from the quark sector would lead to no flavor violation at all. However the evidence of neutrino mass and mixing leads many theorists to posit the existence of right-handed neutrinos at a very large mass scale. With these neutrinos comes a new Yukawa interaction and its accompanying coupling matrix. Though the scale of the new right-handed Yukawa interactions would be far above  $m_W$ , many authors have noted that in SUSY the scalar mass spectrum will still bear an imprint from those interactions thanks to the renormalization group.

In a typical case, one supposes a highly non-diagonal Yukawa matrix, with several  $O(1)$  entries, for the right-handed neutrinos at scales around  $10^{14}$  GeV. In such a case, one finds low energy evidence for the interaction through a variety of channels, particularly  $\tau \rightarrow \mu\gamma$  and  $\mu \rightarrow e\gamma$ , both mediated by gauginos. However there are also related Higgs-mediated processes which will violate lepton number, including:

$\tau \rightarrow 3\mu, \mu ee$ : The leptons that appear in the final state can tell us which entries in the neutrino Yukawa matrix are large and which aren't [9].

$\mathbf{B}_{s,d} \rightarrow \ell\ell'$ : A Higgs-mediated FCNC + Higgs-mediated lepton flavor violation = the ultimate Higgs penguin process! [10]

$H^0, A^0 \rightarrow \ell\ell'$ : Once the heavy Higgs bosons are found, this could be a large effect since it does not suffer from Higgs decoupling effects [11].

### 3. A Useful Probe of Fundamental Physics

A number of authors have commented on the utility of the Higgs penguin for extracting information on more fundamental questions in SUSY and beyond. In fact much can be learned about SUSY from these rare, Higgs-induced processes even without seeing a single superpartner! For example:

- Gauge-mediated SUSY breaking models produce little observable signal of a Higgs penguin. Observation of  $B_s \rightarrow \mu\mu$  at the Tevatron would certainly rule these models out [12].
- Supergravity-type models can produce large signals at the Tevatron, strengthening their position if  $B_s \rightarrow \mu\mu$  is seen.
- We can place model-independent bounds on  $\tan\beta$  and  $m_A$  [13,14] if Higgs penguin effects are observed.
- In the leptonic sector, any channel in which lepton flavor violation is observed corresponds directly to an  $O(1)$  element in the neutrino Yukawa matrix – a matrix which may decouple at  $10^{14}$  GeV!

The flavor sector has often been a source of consternation among theorists working in SUSY, but the Higgs penguin is one example where flavor physics may provide unique opportunities for probing fundamental physics at a deeper level. If  $\tan\beta$  is large, there may be many opportunities to study the Higgs penguin in the next few years and many ways in which it will further our understanding of the electroweak scale and beyond.

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